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The research on discharge coefficient of a non-standard Venturi meter with a swirler

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Abstract

Flow measurement plays an important role in the modern engineering field. And flow rate is one of the most important parameter in this process. One traditional method of deriving flow rate is measuring the pressure difference (DP) along the pipe while the concerned fluid flowing through a DP instrument, such as Venturi meter. This DP instrument is among the most widely used flow measurement instruments, available in plumbing, energy transport pipeline, petroleum chemical industries, etc.
In this research, a non-standard Venturi structure is proposed to satisfy the measurement demand of the inlet multi-phase flow with complex flow pattern. Compared to the standard Venturi meter, the angles of the divergent and the convergent of the proposed device are changed to obtain a shorter pipeline. Besides, a swirler is also placed into the convergent, which would force the flow to swirl with tangential velocity and adjust the inlet gas-liquid two phase flow to annular flow.
The focus of the study is directed toward the pressure profile and the discharge coefficient *Cd* of the proposed structure. Computational simulation of single phase flow is carried out to measure the pressure drop along x-axis via FLUENT. According to the simulation results, the addition of swirler brings an extra pressure drop in advance. At the end of the throat, there is a sudden drop of pressure, decreasing to the lowest point, which is caused by the characteristics of the precession vortex. Then the final static pressure value is obviously lower than the initial static pressure value.

1. Introduction

Flow measurement plays an important role in the modern engineering field, especially in the energy industry. Flow rate is the most important parameter in this process. One traditional method of measuring flow rate is using the difference of pressure head available at the pipe's cross-section area through Bernoulli's equation. Venturi meter is among the most widely used differential pressure (DP) flow measurement instruments, available in plumbing, gas and oil transport pipeline, petroleum chemical industries, etc.

The discharge coefficient *Cd* is defined as a dimension-less number, representing the ratio of actual flow rate to the theoretical flow rate of the DP flow meter. Now a substantial amount of research has been conducted on this coefficient [1-4].

ISO 5167-3 gave the calculation method and the uncertainty of the discharge coefficient for three types of classical Venturi tube. It also proved that if the structure is determined, *Cd* is only related to the Reynolds number [5].

Reader Harris et al. (2000) calibrated fifteen venturi tubes with a wide variety of diameters and diameter ratios in water and high-pressure gas, then obtained an equation of the discharge coefficient related to both Reynolds number and the diameter ratio through the cases in water [6].

Süsser M. et al. (2001) proposed a logarithmic equation between the discharge coefficient and the Reynolds number through a large amount of experiments [7].

Miller et al. (2009) evaluated the effects of an emulsion mixture through venturi tube. They also determined that there is a linear relationship between discharge coefficient and log(*Re*) [8].

Gengtian Liu et al. (2021) conducted a simulation via FLUENT approach to determine the influence of liquid helium temperature on a small-diameter cryogenic Venturi tube. They analyzed the discharge coefficient and found that this dimension -less number increases as the diameter ratio and the incident angle increases [9].

In this research, an computational simulation of single phase flow is carried out to measure the discharge coefficients and pressure profile of the Venturi meter designed by our research group before. Compared to the standard venturi meter, the divergent and the convergent angles of our Venturi pipe are changed to obtain a shorter pipeline, which could obviously reduce the occupied volume of the entire flow meter. The impact of these changes acted on fluid characteristics is studied via FLUENT.

Besides, a swirler is also taken into consider for further research in multi-phase flow. The swirler, composed of several vanes, forces the flow to swirl with tangential velocity. Then the differential density of phases within the multi-phase flow would cause the liquid phase denser to be thrown to the wall, becoming the liquid film. The swirler acts as a device to adjust the inlet flow to annular flow. In this research, by comparing the results of cases of single-phase flow, dry air and water, it can help understand the flow mechanism in this kind of pipeline and find out its impact on differential pressure.

2. Measuring device and measuring principle

2.1 Measuring device

Figure 1 shows the structure of the designed Venturi tube proposed by our research group, which is similar to a swirler meter. It is mainly composed of six parts, the upstream straight pipe, the contraction section, the throat, the diffuser, the downstream straight pipe and the added swirler.

The Venturi's geometric parameters include: pipe diameter D = 50 mm; throat diameter d = 25 mm; the diameter ratio β = 0.5; divergent angle α = 90°; convergent angle θ = 28°.

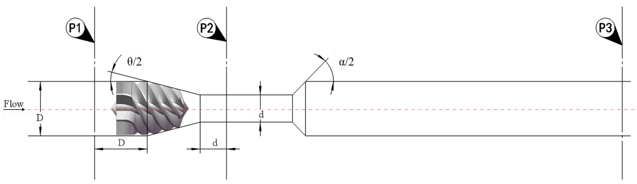

Figure 1: Structure of the designed Venturi pipe.

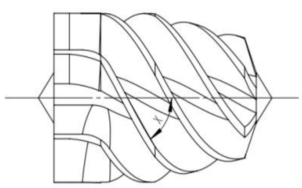

Figure 2: Structure of the swirler.

As shown in Figure 1, three positions along the pipe are chosen to monitor the changing flow pressure. The upstream monitoring point P1 is 1*D* before contraction pipe; and the throat pressure is taken at point P2, 1*d* after the throat entrance; downstream monitoring point P3 is 6*D* (300 mm) after the end of the diffuser.There are six vanes on the swirler, uniformly distributed with a 60° interval, as shown in Figure 2, with X = 65°.

2.2 Measuring principle

According to the Bernoulli's equation, the pressure loss in the horizontal venturi pipe can be described as Equation (1-2):

$$\Delta P_1 = p_1 - p_2 = \frac{\rho_2 u_2^2}{2} - \frac{\rho_1 u_1^2}{2} \tag{1}$$

$$\Delta P_2 = p_1 - p_3 = \frac{\rho_3 u_3^2}{2} - \frac{\rho_1 u_1^2}{2} \tag{2}$$

where *p1*, *p2* and *p3* refer to the pressure of the relating points, respectively. *ΔP1* and *ΔP2* refer to the front pressure loss and total pressure loss.

Together with the mass continuity equation, the theoretical mass flow rate is finally described as:

$$W_{theory} = \varepsilon \times \frac{\pi}{4}\beta^2 D^2 \times \sqrt{2\Delta P_1 \rho} \tag{3}$$

where *W* is the mass flow rate; ε is the expansion coefficient. For compressible flow, ε < 1; for in-compressible flow, ε = 1; *β* is the diameter ratio.

The Bernoulli's equation represents an ideal flow situation. In the actual measurement, the pressure drop would be larger because of the fluid viscosity and flow friction. In fluid mechanics, the discharge coefficient *Cd* is defined as a dimensionless number which represents the ratio of actual flow rate to theoretical flow rate. According to the GB/T2624-2006, the discharge coefficient is given as:

$$C_d = \frac{W_{actual}}{W_{theory}} = \frac{W_{actual}\sqrt{1-\beta^4}}{\varepsilon\sqrt{2\Delta P \rho}\beta^2 D^2}\frac{4}{\pi}. \tag{4}$$

3. Numerical simulatons

In this research, the general purpose computational fluid dynamics solver FLUENT (ANSYS Inc., 2021) is used to implement the simulation of water and dry air in the Venturi pipe, respectively. The air is set as compressible fluid, then the energy equation is automatically added to calculation. Pressure-velocity coupling is accomplished with SIMPLE procedure. RNG k-epsilon model, considered to provide a good calculation accuracy of the strong swirling flow, is chosen to simulate the turbulent process cases with swirler in Venturi pipe. The environment temperature is 20°C and the absolute pressure is 1 atm. The pressure outlet boundary condition used typical downstream operating pressure.

An unstructured computational mesh is created for both two models with or without the swirler, except the converging pipe and swirler parts. Tetrahedral cells occupied these parts because of the complex structure there which is not suitable for hexahedral meshing, as shown in Figure 3. Both geometries contained on the order of 700,000 cells. Standard wall functions are considered in the simulations, then the near-wall cells are generated with appropriate dimensions.

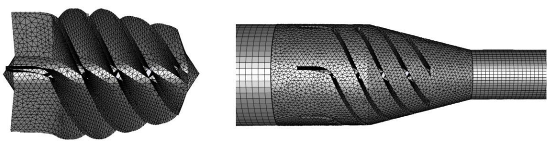

Figure 3: Mesh of the Venturi model.

4. Results and discussion

4.1 The simulation accuracy analysis

To ensure that the cases can give an accuracy results for the flow process, and make sure the calculation accuracy is acceptable, the pressure difference results given by numerical simulation are compared to those of the real flow experiments.

To verify the accuracy of the simulation parameters' setting, the relative error between pressure differences derived from simulation cases and experimental values are calculated, and the ability of the numerical method calculating the complex swirling flow are tested. The results of air and water are shown in Figure 4 and Figure 5, respectively. In these cases, fluid flow through Venturi pipe with swirler in it.

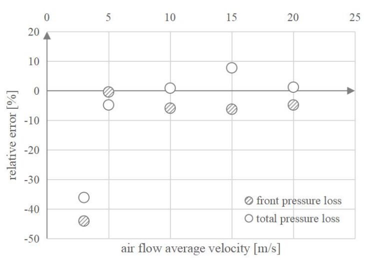

Figure 4: The relative error of pressure loss derived from simulation for air flow cases.

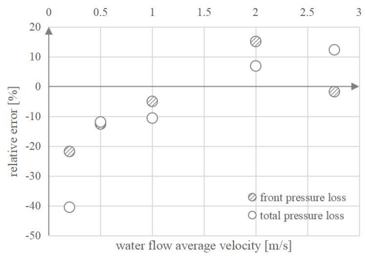

Figure 5: The relative error of pressure loss derived from simulation for water flow cases.

It can be seen from the above that when U_{air} is above 5 m/s, the relative errors are distributed between ±10%. Similarly, when U_{water} is more than 0.5m/s, the relative errors are within ±15%. The overall simulation performance of air cases is better than that of the water cases.

In low-velocity simulation, where the *Re* numbers are around 10,000, the calculation accuracy is severely affected. Many method have been tried to improve the calculation quality here, i.e. increasing the cells number, improving the mesh quality and changing the turbulent model. However, the results are still disappointed. Beyond the simulation accuracy, the reason of this situation could be the instability of the experiment devices with low flow rate, which may caused the deviation of collected DP signal.

4.2 The differential pressure analysis

Figure 6(a)(b) shows the pressure contour of the special-shaped venturi with and without swirler at cross-section area (y=0), when U_{air} is 10m/s, respectively. Figure 7 shows the static pressure curves (gauge pressure) for points near wall along pipe line. The specific analysis of these figures is shown below.

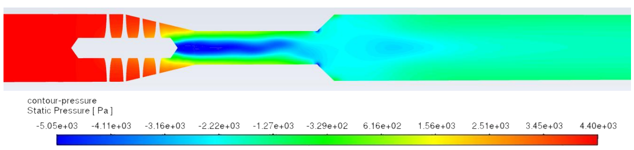

Figure 6(a): The pressure contour of Venturi with swirler.

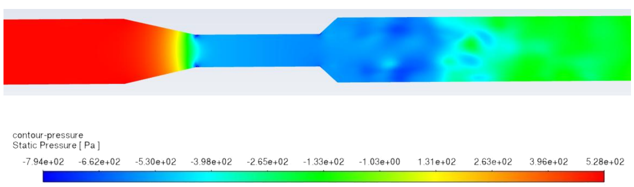

Figure 6(b): The pressure contour of hollow Venturi.

Figure 6: The simulation pressure contour of Venturi pipe with and without swirler, for air case U_{air} = 10m/s.

1) Without Swirler:

It can be seen from Figure 7(a)(b) that the trend of pressure changing of special-shaped Venturi is similar to that of the standard Venturi. When the fluid flows through the contraction section, due to the reduction of cross-section area, the fluid velocity increases and the pressure is significantly reduced. When entering the throat, the pressure reduction trend tends to be gentle, and the static pressure value reaches its minimum at the end of the throat. When fluid flows through the diffuser to the front of the downstream straight pipe section, the pressure first increases sharply, then rises with fluctuations. Finally, the pressure recovers to a relative stable value which is lower than the inlet pressure.

2) With Swirler:

The addition of swirler brings a pressure drop in advance. At the end of the throat, there is a sudden drop of pressure, decreasing to the lowest point, which is caused by the characteristics of the precession vortex. When the fluid enters the diffuser, the pressure recovery process is significantly shorter than that without swirler. The level of pressure is almost stabilizing at the end of the diffuser. During the flow process, there are extra energy loss caused by the swirler, then the final static pressure value is obviously lower than the initial static pressure value.

3) Vortex Precession:

Figure 6(a) demonstrates that vortex is generated after fluid flowing through the swirler. It forms a low-pressure zone (area in dark blue) around the central axis, which contains the center of the vortex core. When the fluid enter the diffuser, due to the sudden increase of flow area, the pressure rises sharply and reverse flow area is formed. Influenced by the reverse flow, the vortex core deviates from the pipe center, approaching the pipe wall. As a result, as shown in Figure 7(c)(d), the near-wall pressure distributions decrease sharply at the end of the throat and drop to a minimum value.

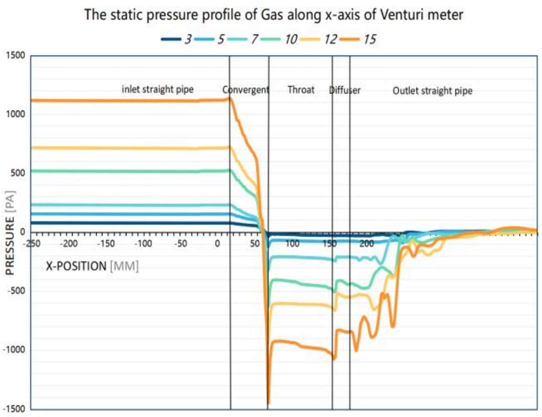

Figure 7(a): Pressure profile of air flowing through Venturi pipe.

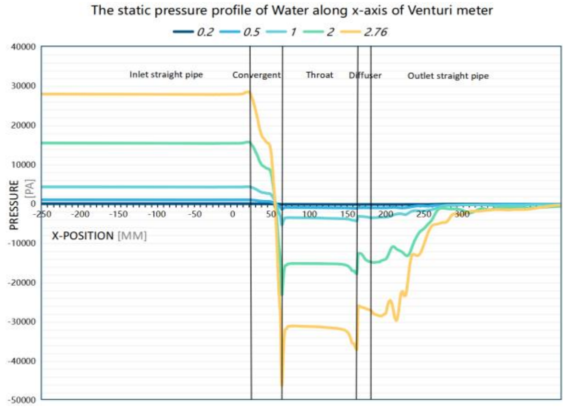

Figure 7(b): Pressure profile of water flowing through Venturi pipe.

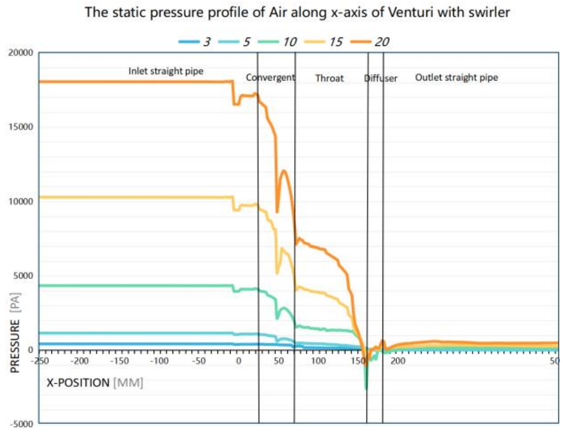

Figure 7(c): Pressure profile of air flowing through Venturi pipe with a swirler.

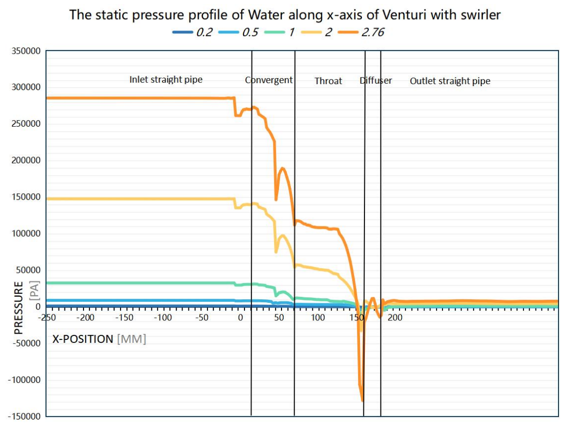

Figure 7(d): Pressure profile of water flowing through Venturi pipe with a swirler.

Figure 7: The static pressure curves (for points near wall along pipe line) of single-phase fluid (air/water with different velocity) flowing through Venturi pipe with or without a swirler.

4.3 The discharge coefficient

The simulation is carried out at the temperature of 20°C and 1 atm operating pressure (absolute pressure). U_{air} changes from 3 m/s to 20 m/s; and

U_{water} ranges from 0.2 m/s to 2.76 m/s, as shown in Table 1. This table also shows the front pressure loss and discharge coefficient of each simulation case. For in-compressible flow, ε = 1, which means ε = 1 for water cases. Then the discharge coefficient of this special-shaped Venturi can be calculated through the front pressure loss derived from water cases according to Equation (4).

Table 1: The front pressure loss and discharge coefficient of air/water simulation cases.

Velo -city [m/s]	Flow Rate [m³/h]	Without Swirler		With Swirler	
		Front Pressure Loss [Pa]	Discharge * Expansion (Cd · ε)	Front Pressure Loss [Pa]	Discharge * Expansion (Cd · ε)
air					
3	21.20	96.56	0.9253	413.90	0.4469
5	35.34	258.87	0.9607	1145.11	0.4478
7	49.48	487.24	0.9612	-	-
10	70.68	988.97	0.9638	2845.32	0.5682
12	84.82	1416.85	0.9663	-	-
15	106.02	2204.01	0.9684	6267.02	0.5743
20	141.37	-	-	10977.2	0.5786
Water (ε = 1)					
0.2	1.41	325.56	0.9589	1257.6	0.4879
0.5	3.53	2023.74	0.9615	5883	0.5639
1	7.07	8037.35	0.9650	21967	0.5837
2	14.14	31942.3	0.9681	87059	0.5864
2.76	19.51	59627.7	0.9778	173863	0.5726
Mean Cd (water cases)		0.9663		0.5589	

The discharge coefficient is proved to be relative to the velocity and density of the concerned fluid. Süsser M. et al. have proposed a logarithmic equation between the discharge coefficient and the Reynolds number. Miller et al. also gave a general analytical expression for the Reynolds-dependent discharge coefficient as shown below:

$$C_d = A\log(Re) + B \,. \tag{5}$$

The Reynolds number of water cases in this research ranges from 10,000 to 138,000. The discharge coefficient increases gently as the *RE* number increases. According to Equation (4), for the special-shaped Venturi pipe without swirler in it, we can give a similar linear fit of this relationship, Equation (6), as shown in Figure 8. The maximum U_{water} is up to 4 m/s in Figure 8, and the *RE* number increases to 200,000 relatively.

$$C_d = 0.0143\log(Re) + 0.8993 \,. \tag{6}$$

The relative error of this fitting is within ±0.5%. In this research, the *RE* number of the gas range from 10,000 to 50,000, which is covered by the reference *RE* number of water. When taking Equation (6) into the compressible air cases, this will help solving *ε* of air in the special Venturi pipe, the results are shown in Table 2.

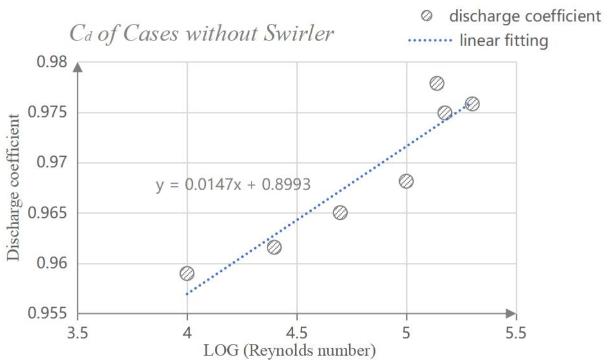

Figure 8: The logarithm relationship between RE numbers and the discharge coefficient for Venturi pipe without swirler.

Table 2: The front pressure loss and discharge coefficient of air/water simulation cases.

Velocity [m/s]	Flow Rate [m3/h]	Without Swirler		
		Predicted Cd	Discharge * Expansion (Cd · ε)	Expansion coefficient ε
3	21.20	0.9582	0.9253	0.9656
5	35.34	0.9616	0.9607	0.9990
7	49.48	0.9636	0.9612	0.9974
10	70.68	0.9659	0.9638	0.9978
12	84.82	0.9671	0.9663	0.9991
15	106.02	0.9685	0.9684	0.9999
Mean value		0.9642	0.9577	0.9932

Compared to the cases without swirler, other cases would be more complex. As shown in Table 1, in these cases, the mean value of *Cd* is only 0.5589. It indicates that the energy loss caused by the swirler is significant and can not be ignored. The reason of this phenomenon is that a majority of the total energy is lost, forming the swirling flow, which causes extra differential pressure. When using the extra pressure to calculate the theory flow rate, it can be incredible larger than it should be originally.

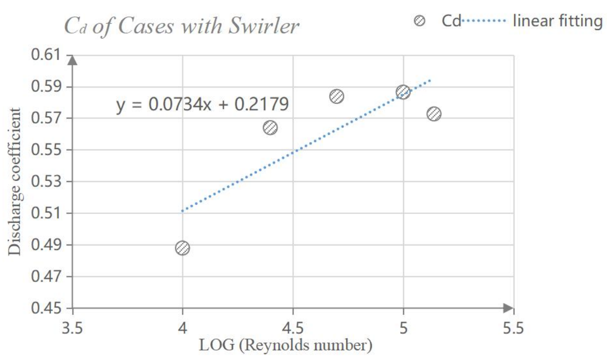

Figure 9: The logarithm relationship between RE numbers and the discharge coefficient for Venturi pipe with a swirler.

Figure 9 shows the linear fitting relationship between the *RE* numbers and the discharge coefficients of the cases with a swirler. The relative error of the fitting is within ±5%. *Cd* first increases as the RE number becoming larger, however, *Cd* suddenly decreases when U_{water} becomes larger than 2 m/s. More simulation will be conducted to study this relationship and the sudden change.

5. Conclusion

In this research, a non-standard Venturi structure is proposed. Besides, a swirler is also placed into the convergent of the pipe, forming a structure similar to the swirl meter. Computational simulation of single phase flow is carried out via FLUENT. The focus of the study is directed toward the pressure profile and the discharge coefficient *Cd*.

Compared to the experiment results, the accuracy of the simulation is acceptable. According to the simulation results, the pressure changing trend of the proposed Venturi pipe without the swirler is similar to the standard Venturi, while the addition of swirler brings an extra pressure drop in advance. At the end of the throat, there is a sudden drop of pressure, decreasing to the lowest point, which is caused by the characteristics of the precession vortex. Then the final static pressure value is obviously lower than the initial static pressure value.

Refer to the previous research on the relationship between *RE* number and *Cd*, a logarithmic fitting equation is proposed via the water simulation cases. In this research, for hollow Venturi pipe, the mean value of *Cd is 0.9663, and the* relative error of the fitting is within ±0.5%. However, as the addition of the swirler, the mean value of *Cd* is only 0.5589, and the fitting relationship is also disappointed. More simulation will be conducted to study the influence of the swirler.

References

[1] P. Banchhor, S. Singh, V. Seshadri, B. Gandhi. Performance characteristics of wedge flowmeter using CFD [J]. Comput. Fluid Dyn., 11(3), pp. 279-284, 2002.

[2] S. Singh, V. Seshadri, R. Singh, R. Gawhade. Effect of upstream flow disturbances on the performance characteristics of a V-cone flow meter [J]. Flow Meas. Instrum.,17(5), pp. 291-297, 2006.

[3] J. Yoon, N. Sung, C. Lee. Discharge coefficient equation of a segmental wedge flow meter [J]. Process Mech. Eng., 222, pp. 79-83, 2007.

[4] F. Dong, F. Zhang, W. Li. Oil-Water Two-Phase Flow Measurement with a V-Cone Meter in a Horizontal Pipe. International Instrumentation and Measurement Technology Conference, Tianjin, China.

[5] ISO 5167: *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 3: Nozzles and Venturi nozzles*, 2020.

[6] M J Reader-Harris, N Barton, W C Brunton, J J Gibson, D Hodges, et al. The discharge coefficient and through-life performance of Venturi tubes. 18th NORTH SEA FLOW MEASUREMENT WORKSHOP, 2000.

[7] Süsser M., Jitschin W. Investigation of the discharge coefficient of small Venturi tubes. Proceedings of the Eighteenth International Cryogenic Engineering Conference (ICEC18), pp.651-654, 2001.

[8] G. Miller, B. Pinguet, B. Theuveny, P. Mosknes. The Influence of Liquid Viscosity on Multiphase Flow Meters, TUV NEL, Glasgow, United Kingdom.

[9] Gengtian L., Junjie L., Lei S., Dazhi K., et al. Numerical analysis of flow performance on small-diameter cryogenic Venturi flowmeter [J].Cryogenics, 02, pp.41-46, 2020.